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Article

The Geography of Solar Photovoltaics (PV) and a New Low Carbon Urban Transition Theory

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Abstract: This paper examines the early phases of a 21st century energy transition that involves distributed generation technologies employing low or zero carbon emission power sources and their take-up within Australia, with particular reference to the major cities and solar photovoltaics (PV). This transition is occurring in a nation with significant path dependency to overcome in relation to fossil fuel use. Tracking the diffusion of solar PV technology within Australia over the past decade provides a basis for assessing those factors underpinning its exponential growth and its associated geography of diffusion. Positive evidence that there are pathways for cities to decarbonise is apparent but there appear to be different pathways for different city forms with lower density suburban areas showing the biggest take-up of household-based energy technologies. This suggests a model for the low carbon urban transition involving combinations of simple technological changes and harder structural changes, depending upon which parts of the urban fabric are in focus. This is being called a New Low Carbon Urban Transition Theory.

Keywords: renewable energy; solar photovoltaics; decarbonising cities; green technology for suburbs; distributed energy generation; urban energy transitions

1. Introduction

Twenty-first century economic and social development will increasingly depend on harnessing energy to support the demands of manufacturing, transport, city building, extractive industry and domestic living. A principal difference with the past, however, is that future development will be constrained in its reliance on fossil fuels (coal, oil and to a lesser extent gas) for two principal reasons: peak oil and climate change mitigation. At the same time, rapid urbanisation will increasingly concentrate energy demands within cities—and it is the convergence of these global mega-processes that is heightening the pressure on cities in developed societies especially to engineer a step change in their sustainable development. Decarbonising the built environment as well as the raft of urban activities and processes that also contribute to its liveability represents major technology and design challenges. There is a broad portfolio of *energy technology options* available in Australia, each with their own particular environmental and economic signatures. The rate of development of a number of the renewable energy technologies is serving to reduce their cost profiles and provide evidence of their level of reliability in different operational settings. Meanwhile the introduction of a price on carbon is now serving to raise the cost of operating heretofore comparatively cheap coal-based power stations. Accordingly, there are now high levels of risk associated with the present energy market, and eco-efficiency performance assessments of different energy technology options for satisfying future electricity demands of cities are increasingly being qualified as 'at the present point in time'.

Urban development in most western societies post the Second World War has been primarily through car dependent low density *urban design* models—creating what has been termed the 'Automobile City' [1–3]. Compared to its predecessor urban forms, the 'Walking City' and 'Transit City', postwar suburbs have a significantly larger carbon footprint, attributable to the nature of the housing (large floorspace, detached) and transport (private car) available to the residents. In an increasingly carbon and resource constrained 21st century, a fundamental energy transition is required. Decarbonising cities requires a joint attack on the energy used in housing and transport, since approximately 20 percent of GHG emissions are from these two sources in Australia [4].

A framework for low carbon technology interventions in urban and suburban forms of the built environment are outlined in Figure 1: the basis for a new low carbon urban transition theory. Innovation is required in at least two significant arenas to enable transition to a low carbon urban future: implementation of new energy technologies and in urban design. Behaviour change represents a third key dimension in a transition to low carbon living [5] but lies outside the scope of this paper. In both technology and urban design arenas, low carbon innovation pathways can be articulated at a range of scales, ranging from regional to individual dwelling. As will be outlined in the following section, renewable and low carbon energy technologies range from large capacity solar, wind and geothermal installations capable of servicing an entire region to precinct scale and building scale technologies—all of which need to be better understood in order to inform the urban development process.

Urban design innovation is also required at a variety of scales. At metropolitan scale, integrated landuse-transport-environment modelling in Australia [4,6,7] and internationally [8] clearly indicate the carbon benefits that accrue to more compact urban forms underpinned by public and active transport. In terms of transport, residents in the inner and middle suburbs of Australian cities are better served with more energy efficient public transit, given the era in which they were established. Car dependency in the outer 'suburban' areas remains a challenge, however. Electric vehicles constitute a pathway to a lower carbon transport future where solar PV-generated electricity in the outer suburbs can form a platform for recharging the cars that are garaged in these areas [9].

However, road congestion will continue to be a challenge until public transit penetrates the outer suburbs more effectively. At dwelling scale, clear pathways have been long established for energy efficient design [10] and delivering carbon neutral housing more recently [11]. Neighbourhood (or precinct) scale carbon assessment of design is also emerging as a new focus for urban designers to examine the performance of alternative scenarios for local area development (greenfields) or redevelopment (brownfields, greyfields) [12,13]. An area where evolution of hybrid low carbon centralised-distributed energy systems are in their infancy.

Figure 1. Model Framework for Low Carbon Technology Interventions in Urban and Suburban Forms of the Built Environment.

		Housing	Transport
Built Environment Fabric	Suburban	• Renewable energy technologies for individual buildings, e.g., solar PV • Precinct scale technologies	• EVs, hybrid, hydrogen vehicles and associated infrastructures • Smart buses
	Urban	• Precinct scale low emission energy technologies, e.g., co-generation; tri-generation	• Public transit • Active transport (walk, cycle) • EVs, hybrid, hydrogen vehicles and associated infrastructures
		Low/Zero Carbon Technologies	

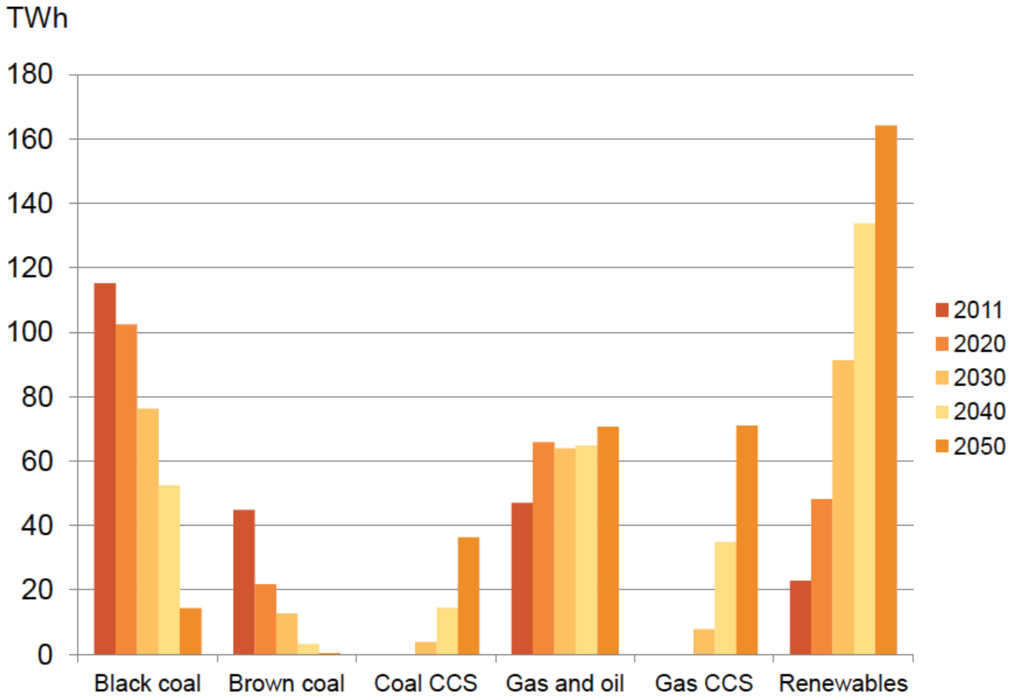
This paper will focus on one of the renewable energy technologies—solar PV and the manner in which it is penetrating cities in Australia. Following a section that places solar PV in its broader energy context, with particular reference to the emergence of distributed generation and PV in particular, subsequent sections of the paper will examine: the policy context in which PV technology has been required to operate; the diffusion of PV technology in Australia—the geography as well as the rate of take-up; the spatial correlates of demand; and key supply side elements, including the cost of PV panels.

The paper then examines in more detail the emerging patterns in the geography of solar PV take-up that lead us to suggest a new model for the low carbon energy transition in cities: different parts of the city are going to have very different pathways to the low carbon future depending on their urban fabric. Whilst this has been recognised by us before in terms of transport fuel [1] this new data suggest that renewable energy will have different pathways as well. The combination of strategies for different urban fabrics we have called a New Low Carbon Urban Transition Theory.

2. Contemporary Energy Challenges and Options: An Overview

Figure 2 illustrates the magnitude of the challenge for countries such as Australia with an energy transition involving a significant decarbonisation of the energy supply. Reports by Garnaut and the IPCC [14,15] call for 80% reductions in CO2 by 2050 in order to prevent global warming exceeding 2 °C by the end of the century. The World Bank [16] is suggesting that a 4° world is becoming a more likely proposition by 2100 unless significant carbon mitigation can be realised. Success in this respect will rely heavily on the eco-efficiencies of technologies attempting to harness solar, wind, geothermal, bio-energy and hydrogen sources of power.

Figure 2. Projected sources of Australian electricity generation under average of 450 ppm and 550 ppm scenarios. Source: [17].



A recent comparative assessment of low emission energy options undertaken from an Australian perspective (see Table 1) suggests that there are 'no quick fixes or easy choices' [18].

Each country and region will view this portfolio differently, given variations in climate, geography of natural endowments (related to hydro, geothermal, wind, solar, as well as fossil fuels), population and settlement configurations, the existing regime of energy industries and associated infrastructures, and government energy policies. For example, a comparison of Australian and Korean low carbon green growth strategies [19] indicates that both countries are heavily dependent on fossil fuels and are planning to expand the contributions that renewable technologies can make to the energy mix in combination with the introduction of a cost to carbon emissions. Australia is a net energy exporter while Korea is almost entirely dependent on energy imports. Korea is focused on developing energy technologies for export whereas Australia is mostly focused on continuing its export of fossil fuels but also with its new Clean Energy Package appears to be beginning to focus on development of renewable technologies to address local requirements [20].

In this context, all zero and low emission energy technologies are prospective for application in Australia with the possible exception of nuclear (despite having large uranium reserves there continues to be political resistance to the development of nuclear power in Australia on environmental and nuclear proliferation grounds). Many of the technologies listed are contenders for large scale power generation which will continue to be located at some distance from cities, albeit in different locations to fossil fuel based power stations (e.g., wind, concentrating solar power, hot rocks, carbon capture and storage) while a smaller number are more applicable to being embedded with built environments as local energy generators—energy for and from the city. Here solar PV and cogeneration have emerged as early favourites for implementation.

Table 1. Comparative assessment of low emission energy technologies in Australia, 2012.

Energy domain	Scaleability	Current costs, trends	Extent of commercial deployment	Prospects for private sector involvement	Government barriers
Wind	Could supply ~ 20% Australia's electricity needs	Potential for rapid scale-up	Significant deployment underway	Significant, given effective subsidy via 20% renewable energy target	Grid infrastructure and system integration needs to be improved; some community resistance to wind farm noise
Solar PV	Could generate >30% with grid integration management and storage	Costs are fair and falling rapidly	Already widespread, but not yet at scale to impact grid	Growing strongly, but dependent on government subsidies	Large-scale deployment constrained by integration with electricity grid
Concentrating solar power	Resource sufficient to meet total national needs; thermal storage and gas cogeneration needed to overcome intermittency	Currently non-commercial; costs likely to decline with development and broader deployment	Some deployment overseas; currently higher cost c.f. wind, solar PV	Some activity in Australia; dependent on government subsidies	Grid infrastructure and system integration need to be improved for remote sites (cf. wind)
Geothermal – hot rocks Geothermal – low temperature heat pumps	Abundant resource could underpin a major contribution	Hot Rocks - Reliability and costs highly uncertain; still at development stage. Low temperature heat pumps – costs low and falling as mass production occurs	Minimal deployment in Australia as hot rocks too far from markets; low temperature geothermal heat pumps in cities beginning; private companies involved in exploration and local heat pump installation.	Investor confidence required for the more difficult hot rocks resource.	More government involvement in resource mapping, grid development and clear regulatory framework. Heat pumps are mainstreamed but links to geothermal resource often not known.
Carbon capture and storage (CCS)	Could contribute significantly and extend life of existing coal and gas plants	Projected costs competitive but not proven; early costs high due to development costs	Only deployed for gas production fields which are less complex than CCS for power generation	Absolute size of investment major barrier for early mover	As above
Nuclear	Could meet a large proportion of national electricity needs	New build costs uncertain as few new plants in last 25 years	Widespread deployment overseas in past, but little recently in high income countries and none in Australia	High costs; significant financial and regulatory risks	Challenge of winning public support as well as legal and regulatory frameworks

Table 1. *Cont.*

Energy domain	Scaleability	Current costs, trends	Extent of commercial deployment	Prospects for private sector involvement	Government barriers
Bioenergy	Significant energy available, although unlikely to be more than 20% of energy demands given competing needs for food. Easy to control short-run output to meet peak daily demand, but some seasonal variation	Not competitive unless supply chain from production to transport improved, likely to take over 10 years. Local customization required, particularly for nature of demand for electricity and heat and feedstock Commercial viability also may be enhanced through improvement to reduce minimum economic scale to <5MW plants	Employed at significant scale in a number of countries and the combustion technology well understood Feedstocks with greatest potential in Australia only deployed in a handful of projects	Several private sector developers already involved in Australia. At current costs, some form of additional government support will be necessary for meaningful levels of project development	Grid infrastructure and system integration needs to be improved to cater for connection of large number of relatively small power stations in regional areas
Cogeneration and trigeneration	Could provide most of the power, heat and cooling in any new urban development	Potential for rapid scale-up once governance worked out	Significant deployment underway in any area wishing to make an immediate reduction in ghg of around 80%	Significant, being driven by a combination of private and local government initiatives	Requires local management rather than centralised utilities; regulations need changing

Source: derived from [18].

3. Government Renewables Policies with Particular Reference to Solar PV

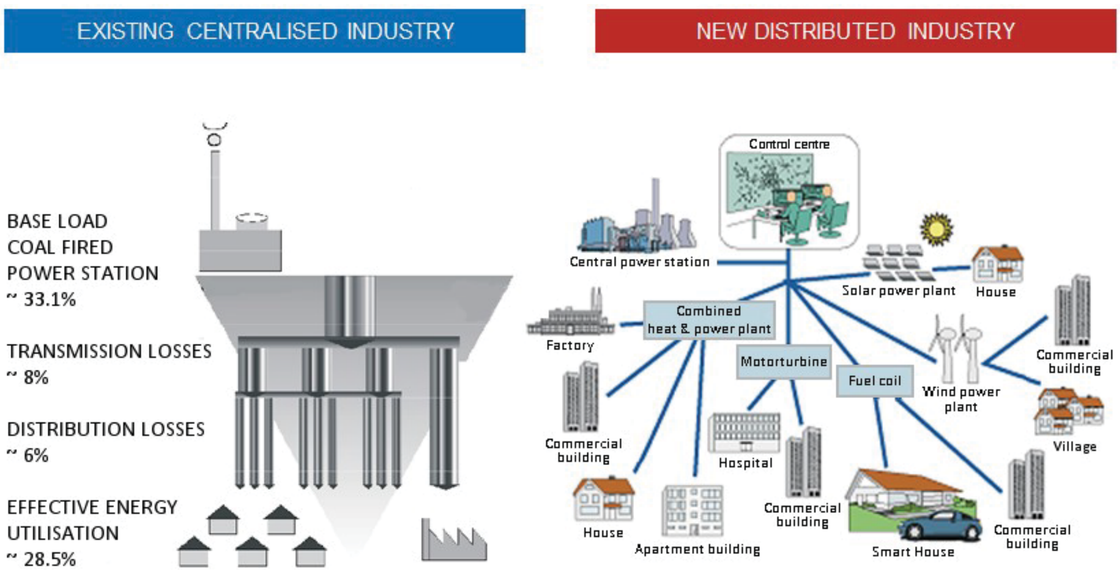
To stimulate a market for renewable energy in Australia, the federal government introduced in 2008 a target of 20% of the nation's energy supply to be sourced from renewables by 2020, amounting to some 45,000 gigawatt hours [21]—the RET. Targeted primarily at encouraging the development of large-scale solar thermal on-grid power stations, domestic solar PV has been more agile in responding to these incentives as well as state government guaranteed feed-in tariffs for electricity sold by households to the grid. The Federal Government's Renewable Energy Certificates (REC's) were rapidly taken up by solar PV providers until a regulation to limit their contributions was passed in 2012 in order to create more assistance for large scale renewables. However, it was an indication that local provision of solar PV had a ready market in Australian homes as shown below where in just a decade the amount of PV in Australia went from 240 MWh to almost 1.8 million MWh. An understanding of the geography of this dramatic take-up can begin to help explain this.

A new political discussion is now suggesting that this growth was due to 'middle class welfare' and a campaign led by *The Australian* newspaper and Business groups such as ACCI and AIG have made calls for the RET to be scaled back because they see it as requiring power retailers to purchase 'more expensive' renewable energy. States are rapidly phasing out their feed-in tariffs because the take-up of PV's has been greatly more than expected. The original 20% RET target remains but Federal assistance is moving more towards large scale renewables. Most of this discussion occurred without any reference to the pattern of diffusion occurring with small scale renewables take-up.

4. Distributed Energy Generation

Historically, virtually all energy used in Australia has been sourced at distance from energy consumers. Fossil fuel fired power stations (coal, oil and gas) collectively supply 95% of the nation's electricity needs [22] and tend to be situated close to the feed stocks, with long distance high capacity transmission cabling being used to connect supply with demand. The energy losses and distribution costs associated with these 'centralised' energy systems are considerable. The carbon emissions are enormous. If Australia is to achieve sustainable growth of its energy supply then alternative energy generation models need to be examined for the roles they can play in meeting the energy needs of communities across the country. Distributed energy generation (DG) represents one such class of models. Distributed energy has been defined [23] as a suite of technologies that aim to reduce the reliance on a centralised supply of energy, reduce emissions and improve energy use efficiency. DG technologies are all relatively small in capacity (less than 30MW) and are typically sited close to the point of consumption—as part of a single building or in a precinct providing energy to a group of buildings (Figure 3). Newton and Tucker [11] have profiled the performance of a range of these small scale local energy generating technologies: solar PV, ground source heat pumps, wind turbines, hydrogen fuel cell and gas micro-turbines in the context of their potential use in delivering carbon neutral or zero carbon housing. In this paper the focus is on the leading small scale energy generation technology in Australia—solar PV.

Figure 3. Centralised *versus* Distributed Energy Generation.



Source: adapted from [23].

5. Market Penetration of Solar PV

Table 2 clearly demonstrates the fact that solar PV is the dominant small scale energy generator in Australia, contributing almost 100% of national output for this category.

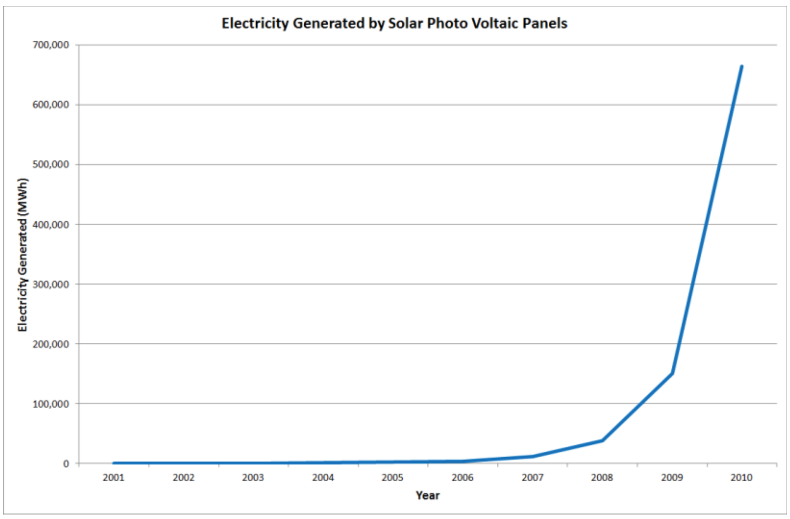
Table 2. Small scale energy generation (MWh) in Australia 2001–2011.

Year Generated	Small Generation Unit (SGU) Source (Deemed) Hydro	Solar panel	Wind	Total
2001	20.8	243.6	31.4	295.8
2002	20.8	813.8	43.4	878.0
2003	20.8	2,052.6	62.2	2,135.6
2004	20.8	3,764.1	96.6	3,881.5
2005	20.8	6,182.7	116.6	6,320.1
2006	41.6	8,577.7	147.2	8,766.5
2007	41.6	16,491.0	165.2	16,697.8
2008	47.2	434,59.3	275.4	43,781.9
2009	75.0	156,341.5	449.2	156,865.7
2010	81.2	678,950.3	1,968.0	680,999.5
2011	133.2	1,792,622.3	2,529.6	1,795,285.1

Source: derived from data supplied by ORER (Clean Energy Australia) [20].

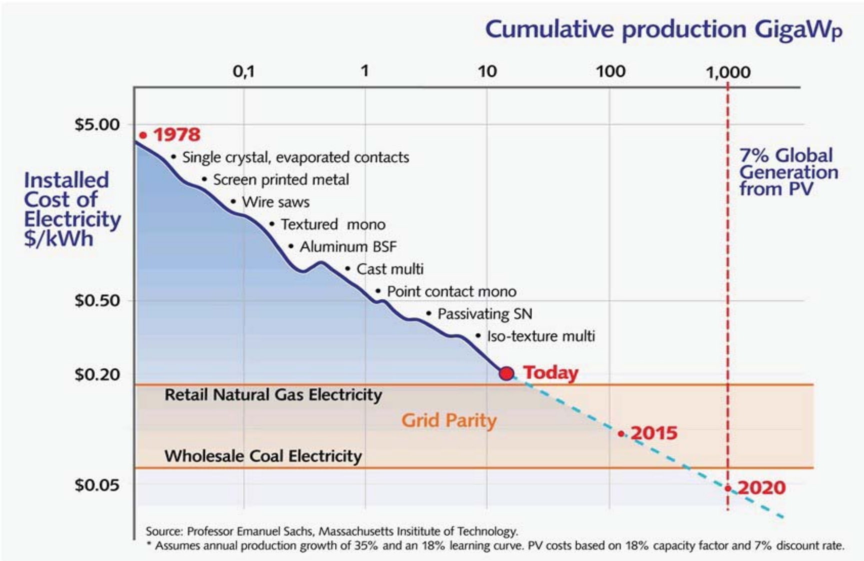
The growth in installed PV capacity has been rapid (Figure 4). A number of the government incentives outlined above have contributed to this trend, but most instrumental has been the decline in price of solar panels to a point where they are approaching parity with the cost of grid-supplied electricity (Figure 5); a price that provides for a payback period now estimated to be four years [24]. Irrespective of whether household motivation for take-up of PV is accessing feed-in tariffs from the grid or offsetting domestic demand around peak rates (to date there is an absence of information on this issue [9]), a satisfactory return on investment represents a clear tipping point for this category of renewable energy capable of sustaining growth without subsidies, especially in a context where electricity prices are forecast to increase rapidly [25,26].

Figure 4. Growth of solar photovoltaic electricity generation in Australia.



Source: derived from data supplied by ORER (Clean Energy Australia) [20].

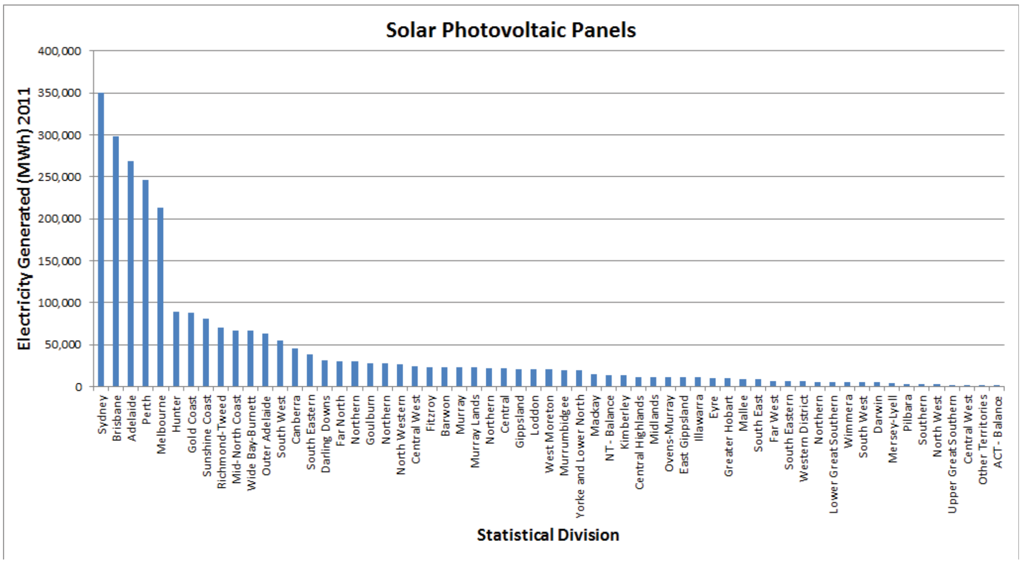
Figure 5. Cost curve for installed photovoltaics. (Source: [26]).



6. Geography of Solar PV Diffusion

Australia's major cities dominate aggregate installed solar PV capacity (Figure 6), although it is also evident that there are a large number of non-metropolitan regions with high levels of PV installation; for example: Hunter, Sunshine Coast, Richmond-Tweed, Wide Bay—Burnett.

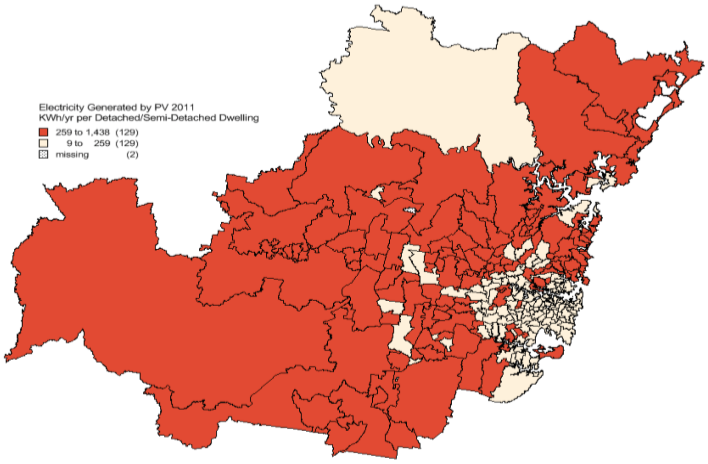
Figure 6. Electricity generated by solar PV by statistical division.



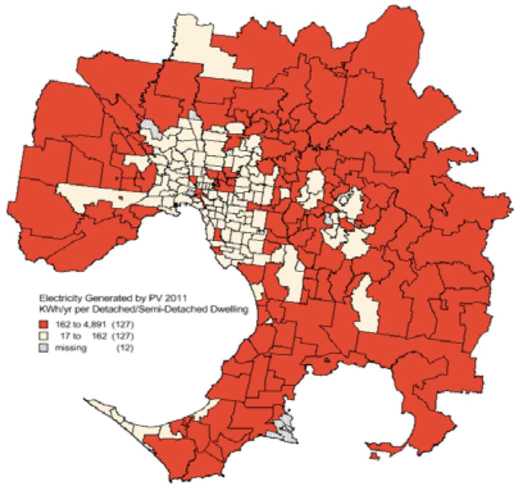
Source: derived from data supplied by ORER (Clean Energy Australia) [20].

The geography of take-up of solar PV *within* Australia's major cities is distinctive (Figure 7a–e). A mapping of postcode areas with above average installed solar PV capacity over the period 2001 to 2011 reveals a clear spatial divide between the suburbs and the inner city, suggesting that PV is emerging as one of a number of new technologies for 'greening the suburbs'. The metric employed here assesses the electricity generated by solar PV per postcode on a per dwelling basis, where only detached and semi-detached dwellings were included in the denominator in order to provide 'equal opportunity' between inner and outer/ higher *versus* lower density postcodes to host PV panels.

Figure 7. (**a**)Installed solar PV capacity in Sydney, by postcode (to December 2011); (**b**) Installed solar PV capacity in Melbourne, by postcode (to December 2011); (**c**) Installed solar PV capacity in Brisbane, by postcode (to December 2011); (**d**) Installed solar PV capacity in Perth, by postcode (to December 2011); (**e**) Installed solar PV capacity in Adelaide, by postcode (to December 2011).



(a)



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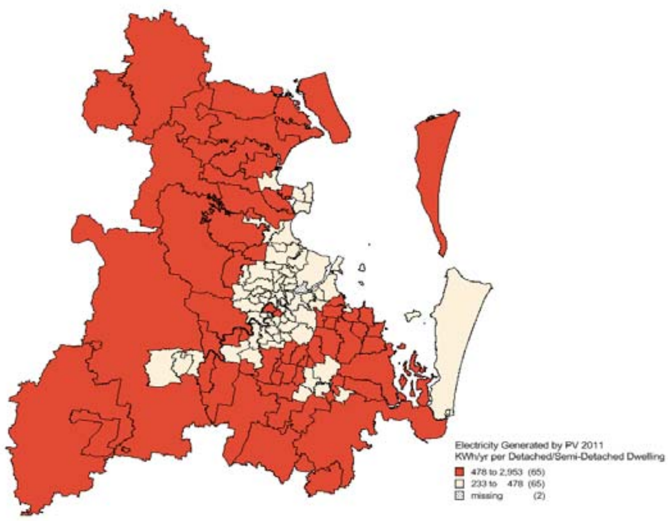
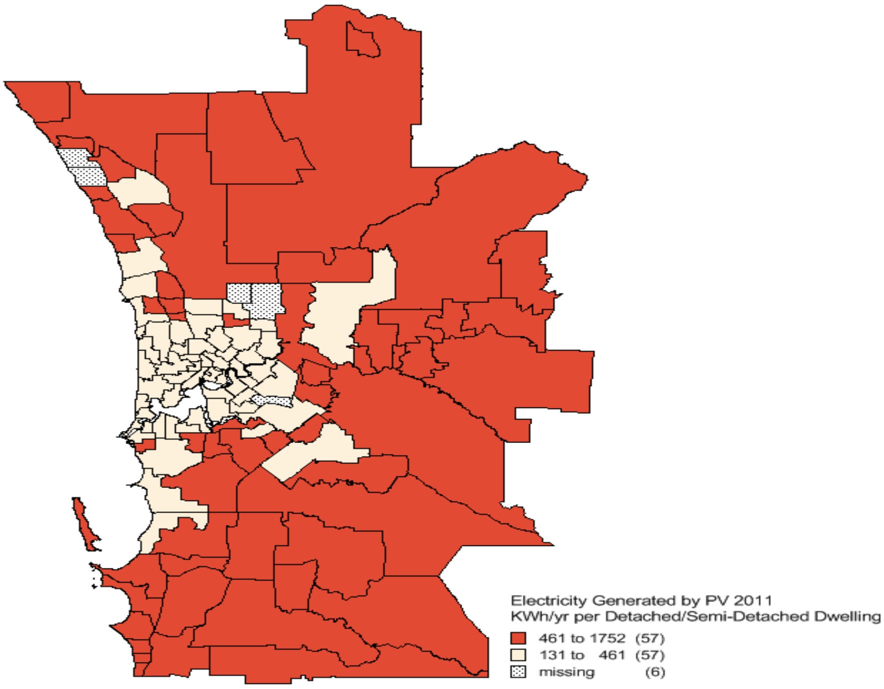


(c)

Figure 7. *Cont.*



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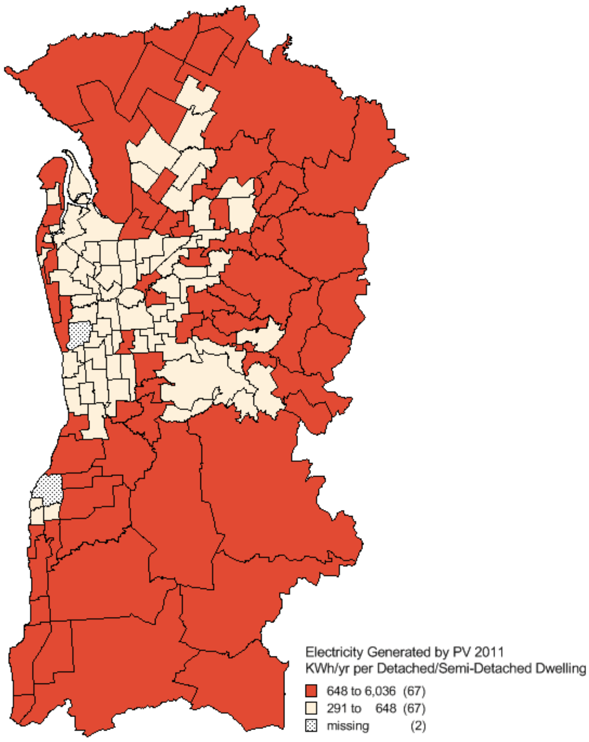
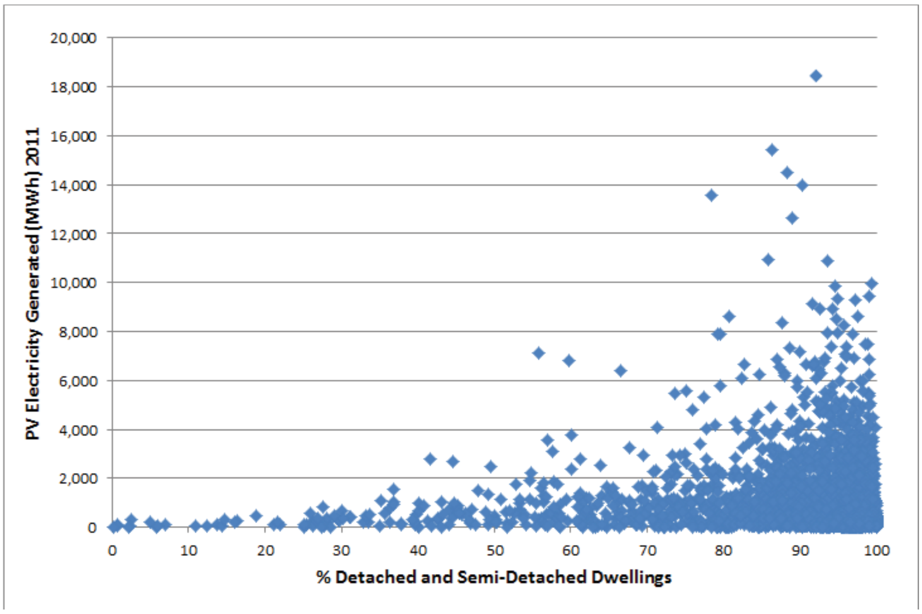


(e)

Source: produced from data provided by Clean Energy Australia [20].

In attempting to understand factors behind the patterns of PV take-up in cities, an absence of data on the characteristics of *individual* households that purchase solar PV, meant that a series of bivariate plots of socio-demographic attributes of all postcode areas in Australia and their PV installed capacity were employed to probe for possible explanations. 2011 ABS census data was employed in these analyses, revealing that dwelling type (detached or semi-detached—see Figure 8) was most closely aligned to PV acquisition, a factor that confirms the proposition made in other studies [9,27,28]. A minimum of appropriately orientated roof space is required to successfully host the necessary number of PV panels to deliver a significant proportion of household electricity demand. It is critical that greenfield subdivisions are developed to maximise solar access to allotments as well as yield, especially given recent trends towards smaller lot sizes and medium density housing [29,30].

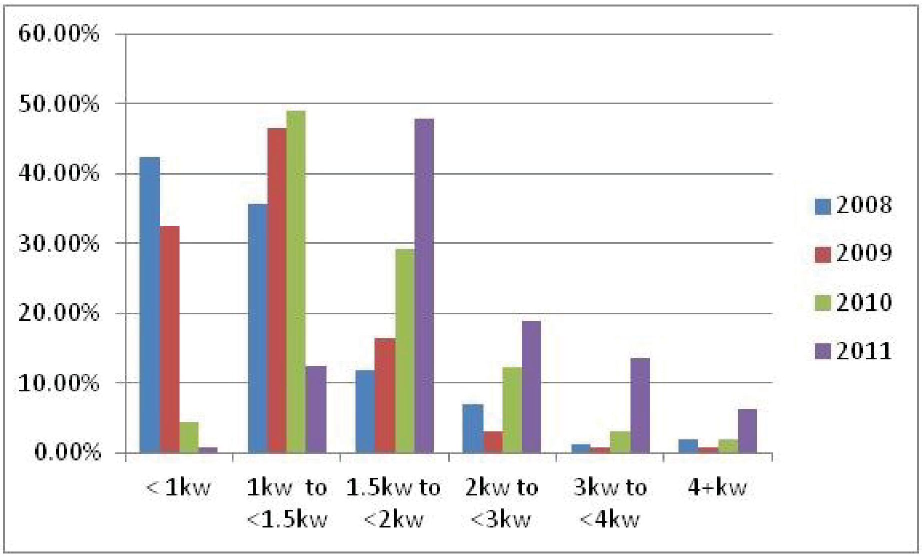
Figure 8. Spatial co-variation between PV installations and percentage of detached or semi-detached dwellings per postcode area.



Source: derived from data supplied by ORER (Clean Energy Australia) [20].

A consistent trend over recent years has been an increase in the size of solar panels being installed in all cities (see Figure 9 for Melbourne data) and that brings with it an increased need for roof space. Audits of roof space are now being undertaken in a number of cities [9,31] to assess the potential capacity for solar PV (earlier papers on 'solar cities' have highlighted the additional space expected to be needed within a metro region to service the requirements of a number of the new energy technology infrastructures when compared against their fossil fuel predecessors [32,33]). Results from these studies are being used in strategic plans to help specify and validate carbon neutrality targets as well as attempting to understand the extent to which surplus PV electricity from some (outer) suburbs can be used to offset peak demands in others (e.g., daytime CBD). The increased demand for domestic PV has also seen the emergence of appeals against developments that would deprive or diminish solar access to neighbouring properties—a new challenge for planning and building regulation. Since all Australian capital city strategic plans are seeking to have between 50 and 70 percent of all new housing supplied by infill in established suburbs—more intensified medium density development replacing the existing physically and environmentally obsolescent detached greyfield housing [34,35]—this will introduce a new tension between two important urban transitions: to more compact cities and to low carbon housing. A resolution rests with more innovative urban design and use of new building materials with PV incorporated in the roofing or wall assembly [36].

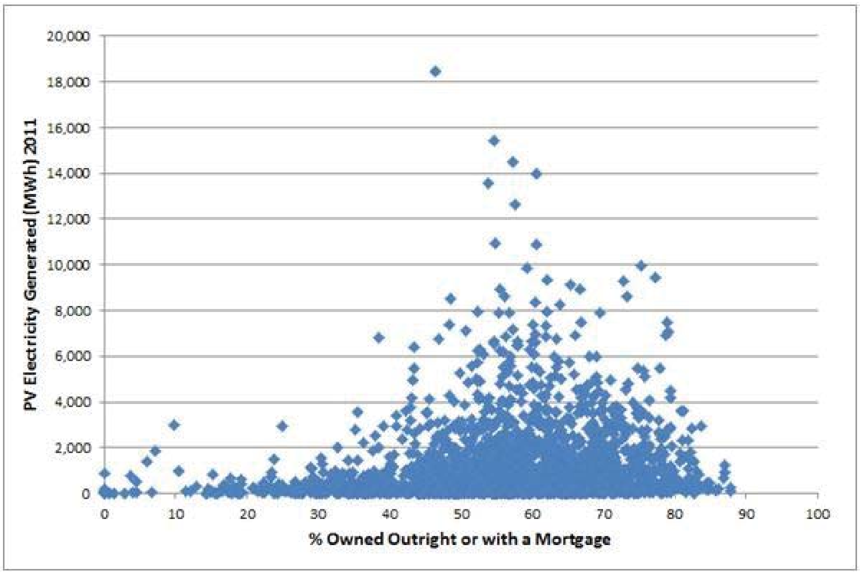
Figure 9. Capacity of installed solar PV systems in Melbourne, 2008–2011.



Source: derived from data supplied from ORER (Clean Energy Australia) [20].

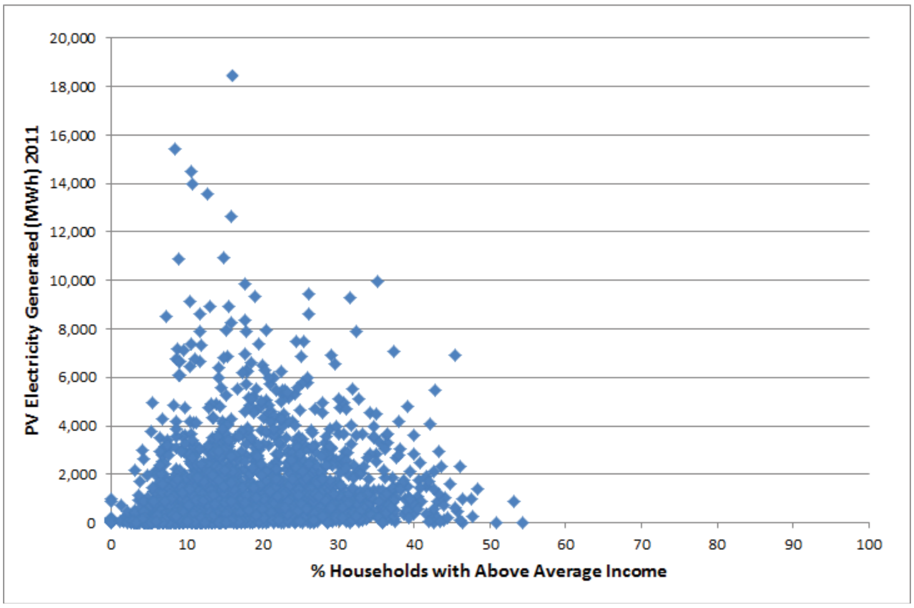
Tenure (here measured by the proportion of households who owned or were purchasing their dwelling) was also featuring as a factor in PV take-up (Figure 10). This is aligned with literature on the effect of split incentives whereby landlords will typically not invest in water or energy saving devices for tenants [37]. Owner occupants on the other hand are in a position to benefit from the savings. Postcode areas with households on above average incomes also were more likely to feature higher levels of solar PV installation (Figure 11).

Figure 10. Spatial co-variation between PV installations and percentage of households who owned or were purchasing their dwelling in the postcode area.



Source: derived from data supplied by ORER (Clean Energy Australia) [20].

Figure 11. Spatial co-variation between PV installations and percentage of households with above average income in the postcode area.



Source: derived from data supplied by ORER (Clean Energy Australia)[20]

The results indicate that the main areas of Australian cities that have responded to the solar PV transition are the outer suburbs. In Australian cities these areas are what Newman and Kenworthy [1] have described as the Automobile City (built around the car, primarily since the Second World War) as opposed to the Transit City (built in the nineteenth and early twentieth century around trams and trains) and the Walking City (built earlier before motorised transport). The Walking City is now mostly high rise and the Transit City is mostly medium density with high rise near stations. The evidence from the spatial analyses presented above and elsewhere [9] suggests that these housing types (apartments and medium density housing) do not lend themselves to PVs at the scale at which they would be needed to make a difference to household energy and carbon budgets.

The fact that the Automobile City's suburbs are making the most of a built environment that lends itself to PVs suggests that there is a pathway for such places to begin to decarbonise. On the other hand Walking City and Transit City areas will find this difficult, as there is just not the space for such technologies to be successfully deployed. Much of our research in the past few decades has been how Transit City and Walking City urban areas have the best urban form to enable a pathway to reduce transport energy use; they can make a response to the carbon-constrained future by using cars less as they have more accessible destinations and greater options for not using a car [1,38] as well as having ideal geography for electric vehicles as distances are much shorter. Thus there is a much clearer pathway for these urban areas to save fossil transport fuel though it is less easy to save dwelling-based power from the (currently fossil fuel-dominated) grid.

In Australia (indeed it is almost certainly a global phenomenon) the past decade has featured sharp rises in the price of both household electricity and transport fuel. These price rises are propelling the transition towards low carbon cities. The results in this paper and the work previously done on low carbon transport scenarios suggest a new theory of urban transition. There are different ways that different urban geographies can respond to reducing carbon as they have different physical constraints caused by their form and infrastructure. There are easy technological substitutions for transport that can be adopted in inner areas where reductions in car use and growth in sustainable transport have been characteristic of the Transit and Walking City areas of Australian cities [1] and there are easy technological substitutions in dwelling energy use that are now becoming feasible for the Automobile City—as shown by the new data presented here. But there will need to be harder structural changes in both areas as well—as outlined below.

7. Energy and Urban Form Revisited—A New Low Carbon Urban Transition Theory

There has been considerable debate about how different urban forms will be able to respond to the challenges of a carbon-constrained world—both for transport and building related energy. The approach suggested here makes a distinction between relatively easy technological changes and more difficult structural changes. The challenges are different for different city areas and city types, which has been outlined before for transport fuels but not for renewable energy. We are thus suggesting that urban fabric will shape the transition to low carbon futures in both transport fuel and renewable energy.

7.1. Automobile City/Outer Suburbs

The data in this study shows a rapid and relatively simple process for the diffusion of solar PV has largely occurred in the outer suburbs of Australian cities, *i.e.*, the Automobile City suburbs. This is likely to continue as the space and cost for installing the technology seems to be available in a way that fits household budgets. To save fossil transport fuel however, the outer suburbs will need more than the household-based approaches that PV is positioned to provide. They will need structural redevelopment (beginning in the middle suburbs) supported by new urban policy and practices in ways that are more likely to enable better transit and active transport modes such as walking and cycling. The prospect of renewable energy being able to supply a significant proportion of the power needs in such areas, including that required by electric vehicles, provides some basis for their future resilience [9]. At present the rate of penetration of hybrid cars in Australian cities is low. Of the total new vehicle registrations in the Melbourne metropolitan area in 2011, only 0.5% of the total were hybrids. Their future growth, if linked to renewable energy sources will help reduce the carbon footprint of automobile transport, but will do nothing to alleviate road congestion, a major problem in Australian cities. Low residential densities are both a villain and a white knight in these suburban regions. The challenges of greyfield precinct *regeneration* (*i.e.* involving housing and associated infrastructures such as energy, water and transport) in the established, middle suburbs of Australia's cities have been outlined elsewhere, together with pathways for intervention [35]. This will not be easy or fast but will be needed to enable a full transition to occur.

7.2. Walking and Transit City/Central and Inner Suburbs

There will be a different set of energy transition pathways for the higher density central and inner suburbs of Australia's cities. They will be more able to adjust to the need to reduce their fossil transport fuel use. They will more easily switch to sustainable transport modes; new light rail lines will be viable as the structural form of the city was built around such technologies. Short distances mean that EV's are already being purchased much more in these areas for the flexible transport needs that cars provide. However, the challenge of these suburbs will be how to reduce their fossil-fuel-dominated power grid needs.

Higher density areas such as these do not lend themselves to the simple provision of PV for every dwelling. However a more structural change can enable such denser areas to participate in a low emissions energy future through the introduction of *precinct scale* energy systems. These energy systems are typically gas powered (natural gas, biogas *etc*.) cogeneration or trigeneration (electricity plus heating and cooling) technologies capable of servicing local areas as long as there are sufficient users within a reasonable distance providing economies of scale. Most of these systems have developed and been applied globally in recent years in denser urban areas more like Walking or Transit City types [39–41]. This is a difficult structural transition for any urban area but the inner areas are more likely to find this process viable as the distances for distribution are short.

Trigeneration is the technology that the City of Sydney is set to introduce, capable of supplying approximately 70% of its electricity requirements by 2030 with a commensurate reduction in CO_2 emissions [42]. The City of Melbourne is currently evaluating options in concert with adjoining municipalities for district scale technology platforms it can implement to deliver its 2020 carbon neutral strategy [43–45]. Similar investigations are also underway for other urban precincts in Australian cities e.g., City of Perth and Stirling City in Perth, Tonsley Park in Adelaide and Macquarie Park in Sydney [39,46]. These systems will be slow to implement just as the redevelopment of the outer suburbs for greater transport fuel efficiency will be slow.

There is some controversy about this strategy as it is not a purely renewable energy strategy unless renewable gas is the source of fuel. However as a transition strategy there is a lot of appeal in being able to deliver base load energy with 70–80% less carbon using available technology when the alternative such as solar thermal is not yet commercially competitive [47]. This may change in the next decade. There are also other environmental issues in play. Although studies [48] have shown that emissions to air from gas micro-turbines are very low at full load, emissions from increased concentrations of cogeneration and trigeneration plants in high density CBD-type environments have had questions raised about their impact on urban air quality, especially when combined with the tailpipe pollution from congested traffic in these zones [49]. Recent studies on urban resource consumption in Australian cities are also demonstrating that different dwelling types, *as designed*, (e.g., detached *vs*. medium density *vs*. high rise) not only vary in relation to carbon emissions (embodied in particular, now there is uniform energy ratings required for all new housing) [4] but performance also varies *when occupied* [50,51]. Here household size matters (energy use/carbon emissions per capita are highest in dwellings with sole occupants) as does household income (viz. energy use increases with income)—a reason why Lenzen [52] suggests domestic energy consumption may be higher in the inner suburbs, where single person households predominate and where household incomes are higher than the metropolitan average.

The New Urban Transition theory enables cities to recognise that simple technological substitution is possible in some parts of the city and deeper structural change is needed elsewhere. Both types of urban fabric outlined here have pathways where they can begin the decarbonisation of their built environment using relatively simple approaches that do not radically change their urban fabric. However, urban planning and technology strategies need to be *tailored* to the specific spatial and structural challenges and opportunities that these different urban fabrics are actually presenting. At least it is now clear that the outer suburbs have a way to begin that builds on their urban form.

8. Conclusion

Australian electricity consumption fell 3.2 per cent over the three years to 2011, ending years of significant increases and projections of future growth in demand. The study by the Renewable Energy Certificate Agents Association [53] found more than half the reduction in power use was due to PV panels, solar hot water systems and other state domestic energy efficiency programs (e.g., light bulb replacement, energy rated appliances, *etc*.). A transition *is* beginning to occur, and solar PV is part of that, though it is mostly in the Automobile City/outer suburbs of Australian cities where there is enough space for these technologies to be effectively introduced. Such areas were often seen to have a major sustainability challenge due to their significant carbon footprints—a combination of large homes (heating and cooling demands) and heavy reliance on oil due to car dependency. Now there is a pathway where they too can begin the decarbonisation transition. The more challenging structural changes needed to create centres accessible by more sustainable transport infrastructures in outer suburbs will be matched by the significant structural changes required in the Walking and Transit City/central and inner suburbs which face challenges associated with the decarbonisation of their higher density buildings. Very little household-based energy change can be initiated directly in these urban forms. Greater reliance will be required of precinct scale distributed energy technologies and their integration into virtual power plants better placed to aggregate power and interface with national grids. Also, new medium density and high rise apartments may well take advantage of emerging building integrated photovoltaics (BIPV) that substitute standard building materials to allow PV to form an integrated part of the building façade (walls as well as roofs). Solar PV is now emerging as a very effective renewable energy technology for decarbonising significant components of our built environment. The geography of transition suggested here enables cities to recognise the combinations of accessible technological change and more difficult structural change required for cities with their different urban forms. It suggests a way forward for any city to participate in the emerging low carbon green economy through a new urban transition theory.

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Conflict of Interest

The authors declare no conflict of interest.

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